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Electrochemical Characteristics of Steel Corrosion in Nano-SiO₂ Modified Recycled Concrete under Dry-Wet Cycles

Yu Li¹, Xinyi Wang² and Deqiang Yang^{3,*}

¹Jiang Xi Hua Da Engineering Quality Test Co. Ltd., Nanchang, China

²Jsti Group Chongqing Inspection Testing and Certification Co. Ltd., Chongqing, China

³School of Civil Engineering and Geomatics, Shandong University of Technology, Zibo, China

*Corresponding Author: Deqiang Yang. Email: yangdeqiang@sdut.edu.cn

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ABSTRACT: To address the insufficient durability of recycled aggregate concrete (RAC) applied in the inland river bridge splash zone under low-chloride salt wet-dry cycling, this study systematically investigated the electrochemical corrosion characteristics of HRB400 steel reinforcement in nano-SiO₂ modified RAC. With recycled coarse aggregate replacement ratios of 0% and 50% and nano-SiO₂ dosages of 0%, 3%, and 6% as key variables, 300 accelerated dry-wet cycle tests were conducted in accordance with GB/T 50082-2009. Open circuit potential (OCP), linear polarization, and electrochemical impedance spectroscopy (EIS) were adopted to characterize the corrosion evolution of steel bars, combined with porosity analysis to clarify the modification mechanism. The results indicated that the passive film of steel in unmodified RAC (C0-R50) failed and initiated active corrosion at approximately 150 dry-wet cycles; 50% RAC incorporation increased the total porosity of concrete from 14.2% to 16.8%, accelerated the diffusion of oxygen and moisture, and significantly elevated the corrosion current density throughout the cycling process. NS modification effectively retarded carbonation-induced depassivation via pozzolanic reaction and micro-filling effect: after 300 cycles, the $|Z|$ of the 3% NS natural aggregate group (C3-R0) reached 1380 $\Omega \cdot \text{cm}^2$, while that of the 6% NS group (C6-R0) maintained 2087.4 $\Omega \cdot \text{cm}^2$, both far exceeding the control group C0-R0 (544.5 $\Omega \cdot \text{cm}^2$). The optimal anti-corrosion performance was achieved by 6% NS dosage, which reduced the final I_{corr} of C6-R0 by 91% compared with C0-R0, lowered the porosity of 50% RAC to 13.6%, and maintained a high charge transfer resistance (R_{ct}) of 10,046.0 $\Omega \cdot \text{cm}^2$ after 300 cycles. Even in the 50% RAC system, 6% NS retained a high $|Z|$ of 2191.1 $\Omega \cdot \text{cm}^2$ at 150 cycles, effectively compensating for the interfacial defects of recycled aggregate. Notably, the C3-R0 group presented a localized impedance peak at 200 cycles, attributed to the temporary accumulation of dense hydration/corrosion products. This study provides quantitative experimental data and a microscopic mechanism support for the engineering application of high-dosage nano-SiO₂ modified recycled concrete in the splash zone of inland river bridges.

KEYWORDS: Recycled concrete; nano-SiO₂; dry-wet cycles; steel corrosion; electrochemical characteristics

1 Introduction

As critical transportation hubs spanning rivers and valleys, highway bridges impose stringent demands on long-term structural durability and service safety. Piers, as key load-bearing components, are persistently exposed to harsh conditions involving cyclic wetting-drying and hydraulic erosion [1]. Particularly in the splash zone, concrete structures undergo periodic immersion-drying cycles and hydraulic impact, leading to accelerated corrosion of embedded steel reinforcement and subsequent cracking and spalling of the concrete cover. This degradation significantly compromises the load-bearing capacity and service

life of the structure [2,3]. Existing durability studies have predominantly focused on marine high-chloride environments, where chloride-induced pitting corrosion is generally recognized as the primary mechanism of steel reinforcement corrosion [4]. However, for the vast inland water systems, the splash zones of bridge piers are typically situated in clean water environments with low or even no chloride ions. In this specific scenario, the corrosion mechanism of steel reinforcement undergoes a fundamental transformation: corrosion is no longer driven by chloride ion penetration, but is mainly controlled by carbonation-induced depassivation caused by CO_2 diffusion and oxygen diffusion process driven by wet-dry alternation [5,6]. Therefore, conducting durability research targeting inland river environments, which is distinct from traditional marine environments, holds significant practical significance for ensuring the safety of inland transportation infrastructure.

Against the backdrop of global sustainable development, the resource utilization of construction and demolition waste has become an inevitable development trend in the construction industry [7]. Recycled aggregate concrete (RAC), which adopts RAC to partially or fully replace natural coarse aggregate (NCA), can effectively reduce solid waste land occupation and fossil energy consumption, thus delivering prominent environmental benefits and economic value [8,9]. Nevertheless, internal microcracks are easily generated inside RAC during the crushing process, and porous residual old mortar inevitably adheres to the aggregate surface. These inherent defects endow RAC with a notably higher water absorption capacity compared with NCA [10,11]. As demonstrated in the experimental work of Younis [12], the full replacement of NCA with RAC brings considerable environmental merits but meanwhile induces severe performance degradation of concrete. Specifically, the workability of RAC declines by 23%, while the compressive strength, flexural strength and splitting tensile strength are reduced by 29%, 19% and 17%, respectively. Such performance deterioration fundamentally originates from the weakened microstructure of the interfacial transition zone (ITZ) in RAC. More critically, under harsh service environments characterized by low-chloride condition and wetting-drying cycles, the inherent pores and microcracks in RAC act as rapid penetration pathways for moisture and oxygen. This phenomenon remarkably accelerates the carbonation rate of RAC and further increases the risk of passivation film failure on steel reinforcement surface.

To enhance the durability of RAC, nano-modification technology has exhibited enormous potential [13,14]. Nano-silica (nano- SiO_2), relying on its high pozzolanic activity and micro-aggregate filling effect, can react with calcium hydroxide to form dense calcium-silicate-hydrate (C-S-H) gel and fill multi-scale pores. These effects can effectively improve the ITZ structure and reduce the permeability of RAC [15–17]. Although other nano-materials such as nano- CaCO_3 and nano- Al_2O_3 also possess modification effects [18–20], nano- SiO_2 is more suitable for engineering popularization due to its better comprehensive balance between cost and effectiveness. Despite existing studies have confirmed that nano- SiO_2 can improve the mechanical properties of RAC [21], and Ying et al. [22] pointed out that it can effectively fill the internal defects of RAC to reduce the chloride ion diffusion coefficient, most of the current researches are limited to chloride-rich environments or conventional performance tests. Few studies have focused on carbonation-dominated corrosion under external chloride-free conditions. Rivera-Corral et al. [23] adopted the method of chloride salt-wetting-drying cycles to investigate the corrosion behavior of plain steel bars and galvanized steel bars. Beglarigale et al. [24] studied the corrosion behavior of different reinforced concrete specimens subjected to systematic wet-dry cycles in natural marine environments.

Current research primarily suffers from inadequate attention to the low-chloride/clean water wet-dry cycling environment of inland river splash zones, insufficient elucidation of the coupling mechanisms between oxygen diffusion-controlled corrosion and carbonation-induced depassivation and their interaction with recycled aggregate defects, and particularly unclear understanding of the corrosion inhibition mechanism of nano- SiO_2 in the absence of external chlorides and its pathway of influencing the carbonation

process through microstructural regulation. To address these gaps, this study simulated the wet-dry cycling environment of inland river bridge pier splash zones in accordance with the GB/T 50082-2009 standard, systematically investigating the effects of different nano-SiO₂ dosages (0%, 3%, 6%) and recycled coarse aggregate replacement ratios (0%, 50%) on the electrochemical corrosion behavior of reinforced concrete after 300 wet-dry cycles. The research focuses on revealing the corrosion inhibition mechanism of nano-SiO₂ under conditions without external chlorides and its regulatory effect on the carbonation-depassivation process through microstructural optimization, aiming to provide theoretical support for the engineering application of this material in inland river bridge splash zones.

2 Experiment

2.1 Raw Materials and Specimen Preparation

The raw materials used in this test meet the requirements of relevant Chinese national standards, and their types and key performance parameters are as follows. P·O 42.5 ordinary Portland cement was adopted, and its chemical composition and physical properties are detailed in Table 1. River sand and crushed stone were used as aggregates. The river sand had a fineness modulus of 2.6 and a mud content of 0.8%. The crushed stone was continuously graded at 5–20 mm, with an apparent density of 2650 kg/m³ and a crushing index of 8.5%. RAC was also continuously graded at 5–20 mm, with an apparent density of 2450 kg/m³, a water absorption rate of 8.2% and a crushing index of 12.6%. Nano-SiO₂ was a grayish-white powder with a particle size of 20 nm, purity ≥ 99%, and specific surface area of 600 m²/g; its dosage was calculated by the mass percentage of the cementitious material. HRB400 hot-rolled ribbed steel bar was used as reinforcement, with a diameter of 12 mm and a length of 100 mm.

Table 1: Chemical composition and physical properties of P·O 42.5 ordinary Portland cement.

Chemical Composition (wt.%)					Physical Properties			
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	Specific Surface Area (m ² /kg)	Water Demand for Standard Consistency (%)	Initial Setting Time (min)	28 d Compressive Strength (MPa)
21.5	5.8	3.2	62.3	2.1	350	26.5	185	48.2

The concrete mix proportion was designed with a target strength grade of C40, a water-binder ratio of 0.45, and a sand ratio of 35%. The detailed mix proportions for different nano-SiO₂ dosages are presented in Table 2. The steel bars were first polished with sandpaper to remove surface oxide scale and rust, then cleaned with anhydrous ethanol to eliminate oil contamination. After air-drying, the ends of the bars were sealed with epoxy resin, leaving only a 70 mm middle section exposed for corrosion testing. The treated steel bars were embedded centrally in 100 mm × 100 mm × 100 mm cubic molds. The concrete mixture was stirred uniformly in a forced concrete mixer, poured into the molds, and vibrated to ensure compaction. After curing for 28 days in a standard curing room (temperature: 20 ± 2°C, relative humidity: ≥95%), the specimens were removed and subjected to accelerated dry-wet cycle corrosion tests. Three parallel specimens were prepared for each mix proportion and steel type to guarantee the reliability of the experimental data. The physical appearance of the finished reinforced concrete specimens used in this test is shown in Fig. 1.

Table 2: Mix proportions of concrete (unit: kg/m³).

Specimen ID	Cement	Nano-SiO ₂	NCA	RAC	River Sand	Water
C0-R0	420	0	1250	0	630	189
C0-R50	420	0	625	625	630	189
C3-R0	407.4	12.6	1250	0	630	189
C3-R50	407.4	12.6	625	625	630	189
C6-R0	394.8	25.2	1250	0	630	189
C6-R50	394.8	25.2	625	625	630	189

**Figure 1:** Photograph of the reinforced concrete specimen.

2.2 Dry-Wet Cycle Test

An accelerated corrosion test was conducted to simulate the actual alternating dry-wet conditions in the splash zone of river bridge piers. The test cycle procedure was set as follows: the specimens were first immersed in water for 15 h, then dried in a constant-temperature environment at 80°C for 4 h, and finally cooled at room temperature for 5 h. A single cycle period was 24 h, and a total of 300 dry-wet cycles were completed in the test to ensure the full simulation of the corrosive environment and the reliability of the experimental data.

2.3 Electrochemical Performance Test Methods

Electrochemical tests were performed using an electrochemical workstation to characterize the corrosion behavior of steel bars. To minimize possible edge effects and crevice corrosion during electrochemical measurements, both ends of the steel bars were sealed with epoxy resin, leaving only the central 70 mm section exposed. Since all specimens adopted identical preparation and sealing procedures, any potential

edge effect was considered systematic and therefore had limited influence on the comparative electrochemical analysis. Before testing, the concrete cover layer was removed by grinding to expose the steel bar as the working electrode, and a three-electrode system was employed, consisting of the steel bar as the working electrode, an Ag/AgCl electrode as the reference electrode, and a platinum sheet as the counter electrode. For the open circuit potential (OCP) test, the system was stabilized for 30 min without external current interference, and the stable potential was recorded; for the linear polarization curve test, linear scanning was conducted within a narrow potential range near the OCP to obtain current-potential response curves, from which the polarization resistance and corrosion current density (I_{corr}) were calculated to quantitatively assess the corrosion rate of the steel bar; for the electrochemical impedance spectroscopy (EIS) test, measurements were carried out over a frequency range of 10^{-2} to 10^5 Hz with an AC amplitude of 10 mV (peak-to-peak), and the impedance data were collected to plot Nyquist and Bode plots.

2.4 Porosity

The porosity of all samples was measured using the water immersion method [25]. All samples were dried at 110°C to remove residual moisture completely. After drying, the samples were transferred to a dry environment, where their dimensions were measured to determine the total volume (V_T), which includes both the solid fraction and the void fraction of the samples.

Each dried sample was immersed in a bucket filled with sufficient deionized water to completely submerge the sample, and the initial water level was recorded. After 24 h of immersion, the sample was carefully taken out of the bucket, and deionized water was added to restore the water level to the initially recorded position. The mass of the added water was measured using a precision balance, which corresponds to the changed volume (V_C).

The porosity (P) was calculated using the following Eq. (1):

$$P(\%) = \frac{V_T - V_C}{V_T} \times 100\% \quad (1)$$

where P is the porosity (%), V_T is the total volume of the sample (mm^3), and $V_T - V_C$ is the void space (mm^3).

3 Results and Discussion

3.1 Evolution of OCP with Dry-Wet Cycles

The variation in open circuit potential (OCP) of steel in reinforced concrete with the number of dry-wet cycles is presented in Fig. 2. All specimens experienced a transformation from a passivated state to an active state. During 0–100 cycles, the OCP values of all groups were higher than -200 mV, indicating an intact passive film and excellent corrosion resistance of the steel bars. With the continuous intrusion of corrosive media, the potential shifted negatively significantly. The unmodified control groups C0-R0 and C0-R50 exhibited a potential drop below -300 mV at approximately 150 cycles, suggesting premature failure of the passive film and the onset of active corrosion. In contrast, specimens incorporating nano-SiO₂ showed remarkable corrosion inhibition. Among them, group C6-R0 maintained a high potential of about -145 mV up to 250 cycles. According to Zhang et al. [26], the incorporation of nano-SiO₂ inhibits the drop in corrosion potential by creating a tortuous path for atmospheric CO₂ and moisture diffusion, which maintains the electrochemical stability of the passive film for a longer duration. A high dosage of nano-SiO₂ significantly improves the compactness of concrete and effectively delays the ingress of carbonation fronts and oxygen. After 300 cycles, the potential values of all groups were lower than -420 mV except for C3-R0, which remained in a transitional corrosion state. This observation indicates that the steel bars in most groups

had generally entered an active corrosion state following carbonation-induced depassivation, particularly in the unmodified recycled aggregate systems where the relatively porous structure offered less resistance to gas permeation.

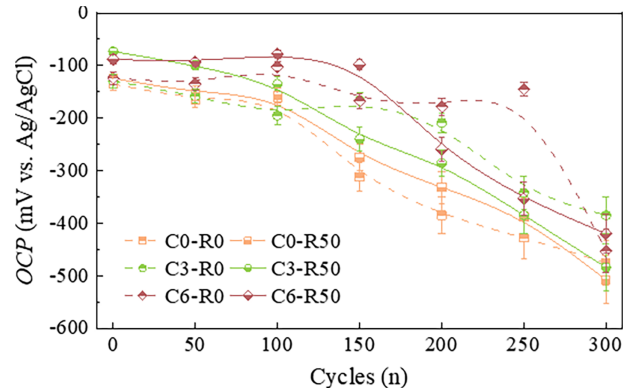


Figure 2: Variation curve of OCP for reinforced concrete.

3.2 Linear Polarization Curve Test

Linear polarization curves of steel bars in specimens with different mix proportions after 0 to 300 dry-wet cycles are shown in Fig. 3a–f. With an increase in the number of cycles, the polarization curves of all groups shift toward lower potential and higher current density, indicating the gradual breakdown of the passive film on the steel surface and the accelerated corrosion kinetics.

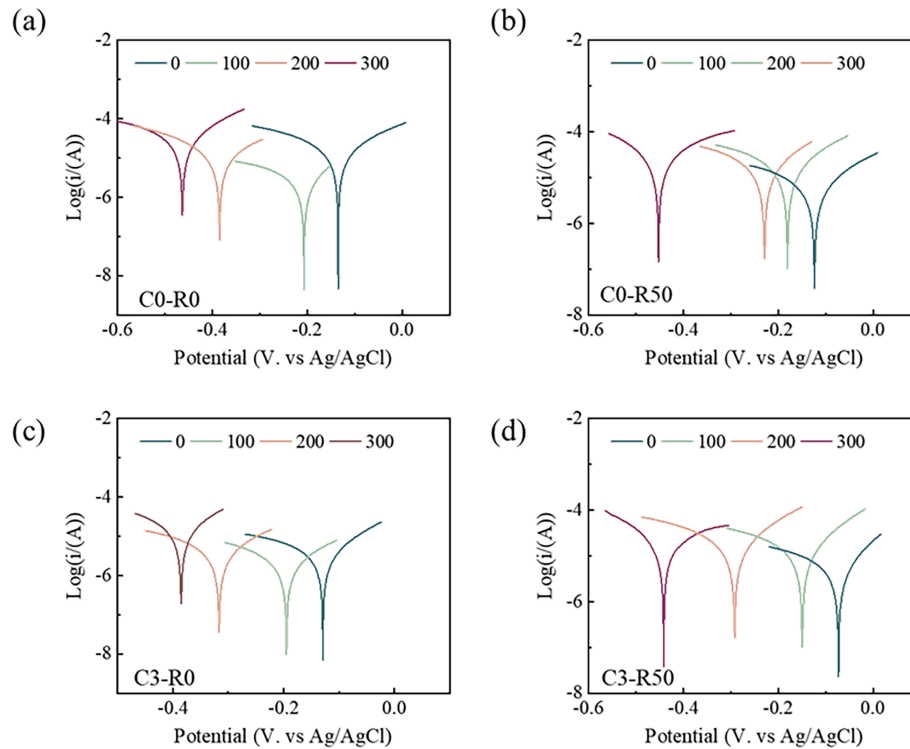


Figure 3: (Continued)

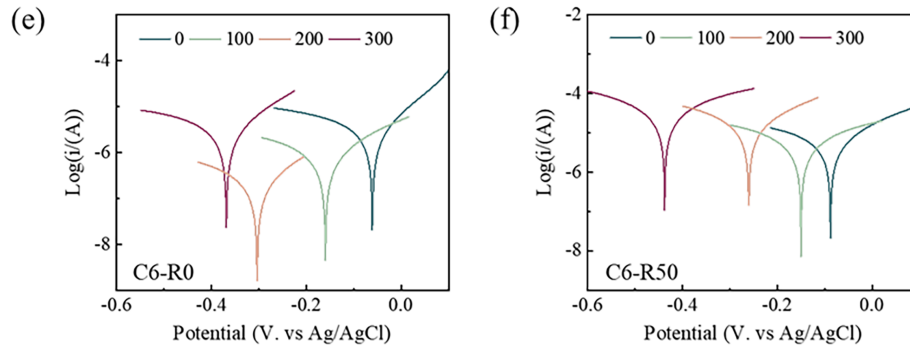


Figure 3: Linear polarization curves of reinforced concrete: (a) C0-R0; (b) C0-R50; (c) C3-R0; (d) C3-R50; (e) C6-R0; (f) C6-R50.

Based on the polarization data, the i_{corr} was calculated using the Stern-Geary Eq. (2):

$$R_p = \left[\frac{d(\Delta E)}{di} \right]_{\Delta E=0} = \frac{b_a b_c}{2.303(b_a + b_c) i_{\text{corr}}} = \frac{B}{i_{\text{corr}}} \quad (2)$$

In the equation, i_{corr} represents the corrosion current density ($\mu\text{A}/\text{cm}^2$). The term B refers to the Stern-Geary constant, the value of which depends on the electrochemical state of the steel: $B = 26$ mV for actively corroding steel, and $B = 52$ mV for steel in a passive state. The expression $\Delta E = E - E_{\text{corr}}$ defines the overpotential, where E is the applied electrode potential, and E_{corr} is the corrosion potential. The parameters b_a and b_c correspond to the anodic and cathodic Tafel constants, respectively, which are associated with the kinetics of the electrode reactions. The polarization resistance, denoted as R_p , is expressed in $\Omega\cdot\text{cm}^2$. The calculated i_{corr} values for all specimens are presented in Fig. 4, which depicts the variation in corrosion rate as a function of nano-SiO₂ content and recycled aggregate replacement ratio under cyclic wet-dry exposure.

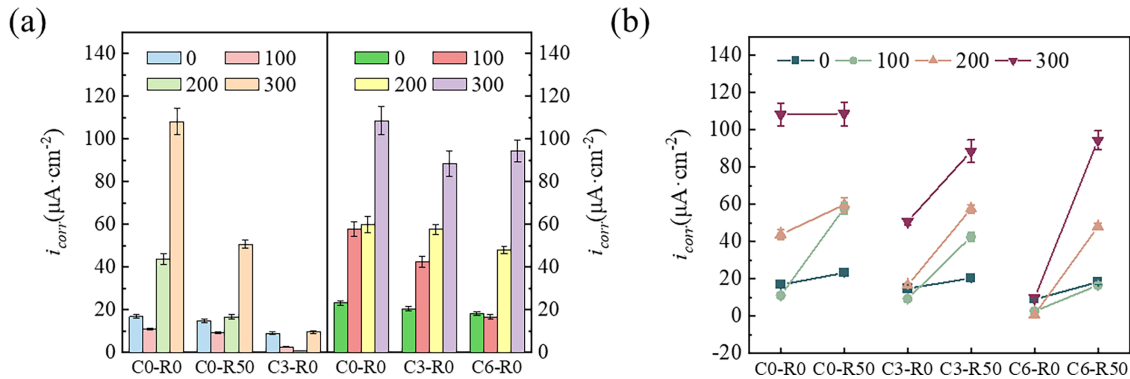


Figure 4: Evolution of corrosion current density (i_{corr}) with (a) RAC replacement ratio and (b) nano-SiO₂ content under wet-dry cycling conditions.

When the replacement ratio of RAC is 0%, the incorporation of nano-SiO₂ exhibits a significant anti-corrosion modification effect. As illustrated in Fig. 4a, the i_{corr} of steel reinforcement shows an overall decreasing trend with increasing nano-SiO₂ content, indicating a distinct corrosion-inhibiting effect of nano-SiO₂ on steel embedded in ordinary concrete, with the effectiveness positively correlated with the dosage. Specifically, after 100 dry-wet cycles, specimens with 3% nano-SiO₂ exhibited an i_{corr} of $9.36 \mu\text{A}/\text{cm}^2$, slightly lower than the $11.12 \mu\text{A}/\text{cm}^2$ of the reference group (C0-R0). However, the corrosion inhibition performance

gradually deteriorated in subsequent cycles, rising to $50.80 \mu\text{A}/\text{cm}^2$ after 300 cycles. This attenuation may be attributed to the insufficient pore-filling capability and insufficient refinement of the ITZ at the lower nano-SiO₂ dosage. As the dry-wet cycles progressed, the increased connectivity of the internal pore structure likely facilitated the ingress of corrosive agents, thereby accelerating the corrosion process. In contrast, specimens incorporating 6% nano-SiO₂ demonstrated superior corrosion resistance throughout the entire testing period. The initial i_{corr} was only $9.06 \mu\text{A}/\text{cm}^2$. This superiority became more pronounced as the cycles proceeded. After 200 cycles, the i_{corr} of the C0-R0 group increased to $43.88 \mu\text{A}/\text{cm}^2$, whereas the C6-R0 group maintained an extremely low value of $0.78 \mu\text{A}/\text{cm}^2$. After 300 cycles, the C6-R0 group recorded i_{corr} of $9.70 \mu\text{A}/\text{cm}^2$, representing a substantial reduction of approximately 91% compared to the reference group ($108.25 \mu\text{A}/\text{cm}^2$), demonstrating a strong long-term protective effect. This finding suggests that high nano-SiO₂ dosages significantly refine concrete's pore structure and densify its ITZ via micro-filling and pozzolanic reactivity, effectively inhibiting corrosive agent ingress and steel electrochemical corrosion. This aligns with Ali et al. [27], who reported that nano-SiO₂ suppresses i_{corr} by densifying the ITZ, thereby limiting electrolyte and oxygen availability at the steel-concrete interface. When the RAC replacement ratio is 50%, nano-SiO₂'s modification effect is markedly diminished. RAC's inherent defects—including porous adhered old mortar and internal microcracks—significantly impair nano-SiO₂ efficacy; even with nano-SiO₂ addition, fully compensating for RAC-induced increased porosity and ITZ degradation remains challenging, resulting in notably inferior corrosion protection compared to non-RAC concrete.

As shown in Fig. 4b, in the absence of nano-SiO₂, the steel in the C0-R0 group ($R = 0\%$) remained in a passive state during the initial corrosion stage, with slow corrosion development. In contrast, noticeable corrosion was observed in the C0-R50 group ($R = 50\%$) after 100 wet-dry cycles. This kinetic acceleration in i_{corr} is highly consistent with the OCP results in Fig. 4a, where the C0-R50 group showed a rapid negative shift in potential early in the cycling process, signifying a high thermodynamic susceptibility to depassivation. This is attributed to the high porosity of RAC, which accelerates the penetration of oxygen and moisture, thereby destroying the passive film on the steel surface. During the later stages of cycling, the corrosion current densities of the two groups converged, suggesting that, in the absence of nano-SiO₂, RAC primarily accelerates corrosion initiation, whereas its influence on the steady-state corrosion rate is limited. With the incorporation of 3% nano-SiO₂, the i_{corr} of the specimens without RAC ($R = 0\%$) remained lower than that of the specimens with RAC ($R = 50\%$) throughout the test period. However, the difference between the two groups gradually diminished as the number of cycles increased, further indicating the limited modification effectiveness of the lower nano-SiO₂ dosage in mitigating the inherent drawbacks of RAC. With a 6% nano-SiO₂ dosage, the specimens without RAC (C6-R0) maintained a relatively low i_{corr} of $9.7 \mu\text{A}/\text{cm}^2$ even after 300 cycles, which was significantly lower than that of the specimens containing RAC (C6-R50). Crucially, the ability of C6-R0 to maintain such a low i_{corr} aligns with its OCP remaining above the critical threshold of -350 mV for nearly the entire test duration, providing a dual-verification of its superior corrosion resistance.

This result demonstrates that although a high dosage of nano-SiO₂ can partially optimize the pore structure and improve the interfacial properties of recycled aggregate concrete, the intrinsic defects of the RAC itself continue to constrain the overall modification effectiveness. Consequently, the corrosion rate of steel in concrete containing RAC consistently exceeds that in concrete without RAC. This further confirms that the RAC replacement ratio is a key factor influencing the modification efficiency of nano-SiO₂, a finding consistent with previous research reporting that RAC significantly increases the porosity of concrete [28].

The formula for calculating mass loss is given as follows: is shown in the Eq. (3).

$$m = \frac{MI_{\text{corr}}t}{\rho nF} \quad (3)$$

In the equation, M denotes the relative atomic mass of iron ($55.85 \text{ g}\cdot\text{mol}^{-1}$), ρ is the density of iron ($7.87 \text{ g}\cdot\text{cm}^{-3}$), I_{corr} represents the corrosion current (A), t stands for the corrosion time (s), n is the number of electrons transferred ($n = 2$), and F refers to the Faraday constant ($96,500 \text{ C}\cdot\text{mol}^{-1}$).

The cumulative mass loss curves of corroded steel bars are presented in Fig. 5, and their variation trends are highly consistent with the electrochemical test results. All specimens entered an accelerated corrosion stage after 20 dry-wet cycles, and the slope of the mass loss curve increased significantly. At the same nano-SiO₂ dosage, the mass loss of the 50% recycled aggregate group was higher than that of the natural aggregate group (R0), because the internal microcracks and high porosity of recycled aggregate provide diffusion channels for corrosive media. The mass loss of group C6-R50 (0.187 g) was higher than that of C6-R0, but lower than that of the unmodified group C0-R50 (0.215 g), indicating that nano-SiO₂ can effectively compensate for the structural defects of recycled aggregate, reduce the section loss of steel bars, and improve the structural durability reserve.

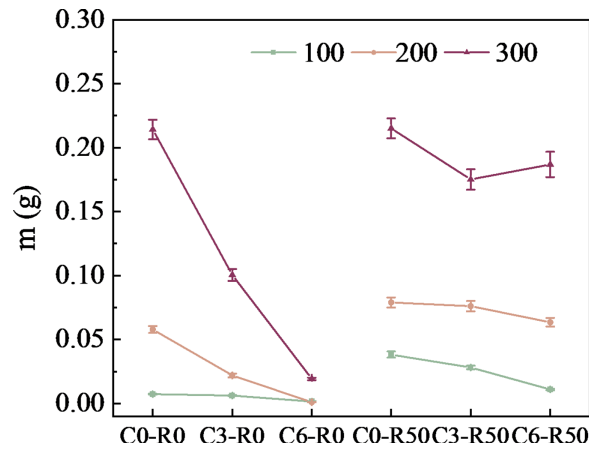


Figure 5: Cumulative mass loss of steel bars with dry-wet cycles.

3.3 Electrochemical Impedance Spectroscopy (EIS) Results

Fig. 6 shows the EIS responses of reinforced concrete specimens under dry-wet cycles. The impedance data were fitted with the two-time-constant CPE equivalent circuit in Fig. 7, where R_s is the solution resistance of the concrete pore solution and electrolyte. R_f and CPE_f in parallel represent the passive film/corrosion product layer resistance and its non-ideal capacitive CPE, correcting the dispersion effect from surface roughness. R_{ct} and CPE_{dl} in parallel denote the charge transfer resistance (a higher value indicates a lower corrosion rate) and the double-layer CPE, describing the non-ideal capacitance at the steel-solution interface [29]. Notably, a higher R_{ct} corresponds to greater interfacial resistance against electrochemical reactions, indicating slower charge exchange and a lower corrosion rate; correspondingly, a larger low-frequency impedance modulus $|Z|$ reflects a denser protective barrier and weaker penetration of aggressive ions. As corrosion progresses, the gradual breakdown of the passive film reduces both R_{ct} and $|Z|$, accelerating the charge transfer process and exacerbating steel corrosion.

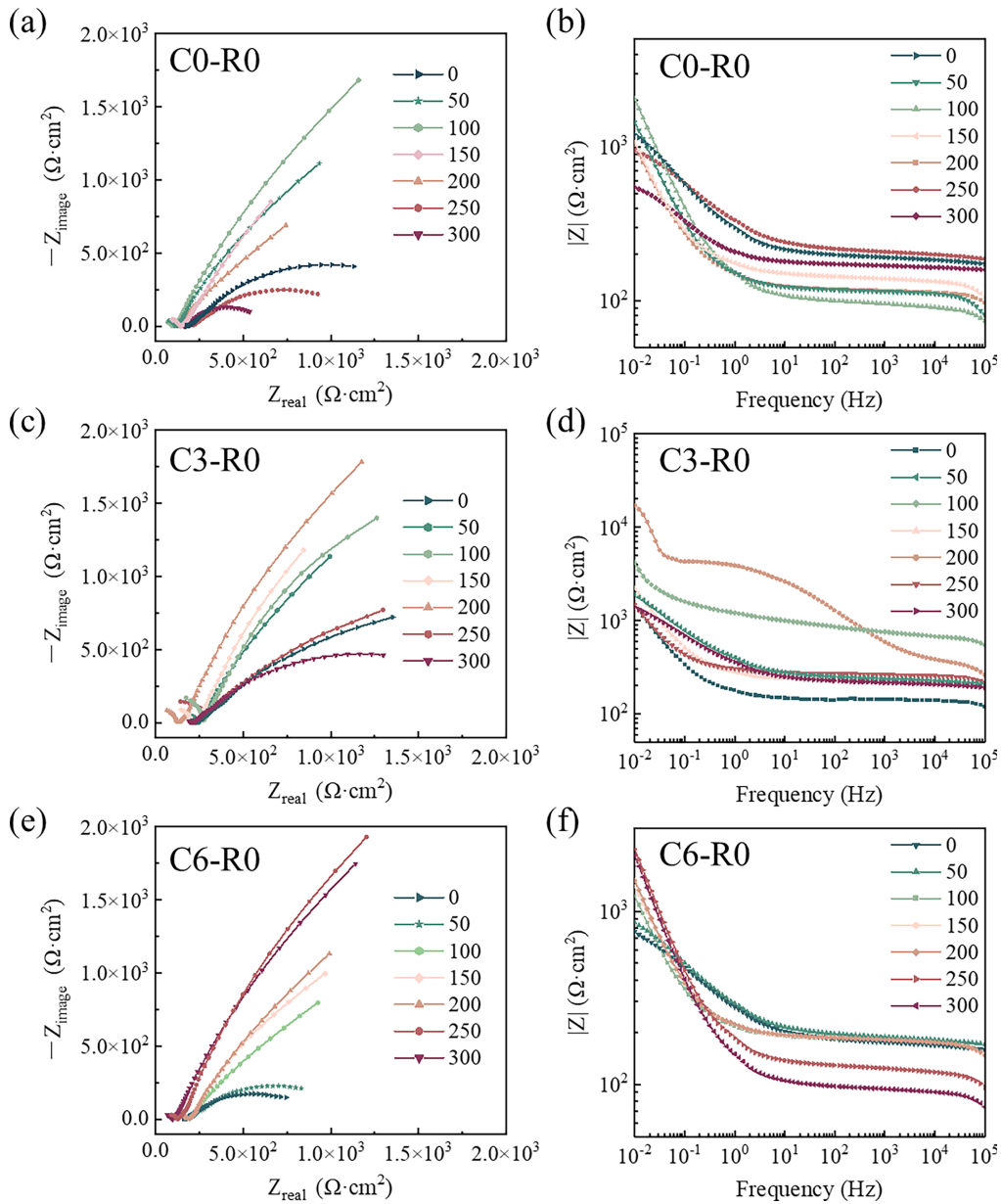


Figure 6: EIS responses of reinforced concrete specimens without RAC during dry-wet cycles: nyquist and bode plots for (a,b) C0-R0, (c,d) C3-R0, and (e,f) C6-R0 groups.

The EIS evolution of groups C0-R0, C3-R0, and C6-R0 under 300 dry-wet cycles is illustrated in Fig. 6. For the control group C0-R0 (Fig. 6a,b), an initial enhancement in corrosion resistance was observed during 0–100 cycles due to continuous cement hydration, with R_{ct} rising from 1164.2 to 7193.1 $\Omega\cdot\text{cm}^2$ and $|Z|$ increasing from 1203.66 to 2043.9 $\Omega\cdot\text{cm}^2$. However, a critical turning point occurred at 150 cycles; carbonation-induced depassivation ($\text{pH} < 11$) caused R_{ct} to plummet to 2350 $\Omega\cdot\text{cm}^2$. By 300 cycles, intensified corrosion reduced R_{ct} and $|Z|$ to 231.7 and 544.5 $\Omega\cdot\text{cm}^2$, respectively, indicating an active dissolution stage. In contrast, the C3-R0 group (Fig. 6c,d) exhibited a distinct three-stage evolution. The pozzolanic effect of 3% nano-SiO₂ initially boosted R_{ct} to 5092 $\Omega\cdot\text{cm}^2$ and $|Z|$ to 4153.76 $\Omega\cdot\text{cm}^2$. Although carbonation reached the steel interface at 150 cycles, a “pseudo-densification” peak appeared at 200 cycles due to corrosion products

blocking the pores ($|Z|$ reached $17,089.9 \Omega \cdot \text{cm}^2$). After 300 cycles, its residual R_{ct} ($2020 \Omega \cdot \text{cm}^2$) remained substantially higher than that of C0-R0, confirming the retarding effect of nano-SiO₂ on electrochemical corrosion. The C6-R0 group (Fig. 6e,f) demonstrated the most exceptional long-term stability. Microstructural optimization by high-dosage nano-SiO₂ promoted passive film growth, with R_{ct} increasing from 703.1 to $4173 \Omega \cdot \text{cm}^2$ during the first 200 cycles. Notably, C6-R0 exhibited remarkable resilience during the final 250–300 cycles, where R_{ct} peaked at $12,951 \Omega \cdot \text{cm}^2$ and maintained a high value of $10,046 \Omega \cdot \text{cm}^2$ at the end of testing. Its final $|Z|$ ($2087.4 \Omega \cdot \text{cm}^2$) was approximately 3.8 times that of C0-R0, evidencing that a dense physical barrier effectively shields the steel from aggressive media ingress.

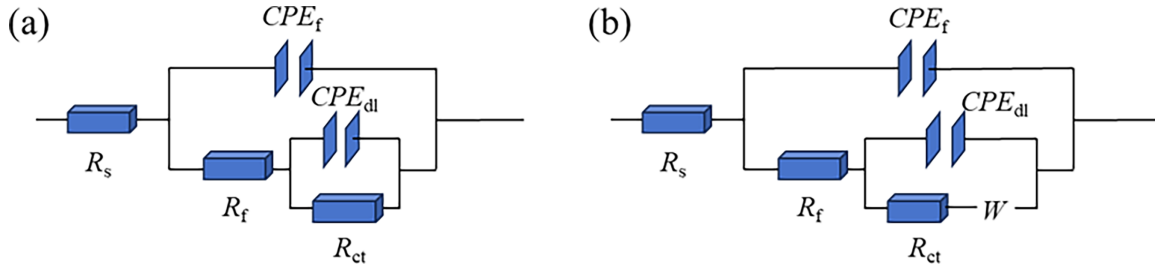


Figure 7: Equivalent circuit diagrams: (a) rebar in a passivated state; (b) rebar in a corroded state.

Overall, the incorporation of nano-SiO₂ significantly enhances the corrosion resistance of reinforced concrete by densifying the cementitious matrix through its pozzolanic effect, thereby creating a tortuous physical barrier that effectively retards the ingress of aggressive media and maintains the long-term stability of the steel's passive film.

The EIS responses for reinforced concrete specimens with RAC are presented in Fig. 8. Group C0-R50 (Fig. 8a,b) exhibited premature aging and insufficient long-term durability; while cement hydration initially led to a peak R_{ct} of $6749 \Omega \cdot \text{cm}^2$ (0–100 cycles), the inherent structural deficiencies of RAC triggered a “free-fall” decline in protective capacity after 150 cycles. By the 300th cycle, its R_{ct} plummeted to merely $807 \Omega \cdot \text{cm}^2$ (less than 12% of its peak) and $|Z|$ dropped to $917.5 \Omega \cdot \text{cm}^2$, indicating extensive passive film damage via the synergistic action of carbonation and moisture. Incorporating nano-SiO₂ in Group C3-R50 (Fig. 8c,d) initially compensated for RAC defects, boosting impedance during the first 100 cycles. However, the weak ITZ eventually became a preferential pathway for ion penetration, resulting in a terminal R_{ct} and $|Z|$ of only $564.6 \Omega \cdot \text{cm}^2$ at 300 cycles. This suggests that 3% nano-SiO₂ is insufficient to offset the structural deterioration caused by a 50% RAC replacement. In contrast, C6-R50 (Fig. 8e,f) demonstrated superior early-stage performance (0–150 cycles), where the high dosage of nano-SiO₂ significantly refined the RAC matrix, increasing R_{ct} from 1877 to $8743 \Omega \cdot \text{cm}^2$ and $|Z|$ to $2191.1 \Omega \cdot \text{cm}^2$. Nevertheless, after 200 cycles, the group entered a degradation stage, with R_{ct} and $|Z|$ final values reaching 1044 and $920.7 \Omega \cdot \text{cm}^2$, respectively. This trend aligns with the OCP evolution in Fig. 2, confirming that while 6% nano-SiO₂ improves the matrix, it cannot fully eliminate the adverse effects of complex ITZs under long-term dry-wet cycling, which ultimately serve as penetration channels that weaken the passive film stability.

The variations of R_{ct} and $|Z|$ for all groups (Fig. 9) intuitively reflect the differences in corrosion evolution among specimens with various mix proportions. Nano-SiO₂ significantly enhances the initial stability of the passive film on the steel surface and delays its degradation. Taking the natural aggregate (R0) group as an example, after 300 dry-wet cycles, the $|Z|$ of C3-R0 and C6-R0 reached 1380 and $2087.4 \Omega \cdot \text{cm}^2$, respectively, which were much higher than that of the control group C0-R0 ($544.5 \Omega \cdot \text{cm}^2$). This phenomenon can be attributed to the dual effects of nano-SiO₂: on the one hand, the “nucleation effect” of nano-SiO₂ promotes the uniform coverage of hydration products on the steel surface; on the other hand, its high

pozzolanic activity consumes $\text{Ca}(\text{OH})_2$ at the interface, generating C-S-H gel with a more stable structure. The dense microstructure formed by these effects provides effective physical shielding for the steel passive film, retarding the penetration of the CO_2 and moisture and thus delaying the film degradation. Notably, the C6-R0 group exhibited an upward trend in $|Z|$ even at 250 cycles (reaching $2275.16 \Omega \cdot \text{cm}^2$), indicating that high-dosage nano- SiO_2 has strong long-term modification potential and can provide durable protection for the steel passive film.

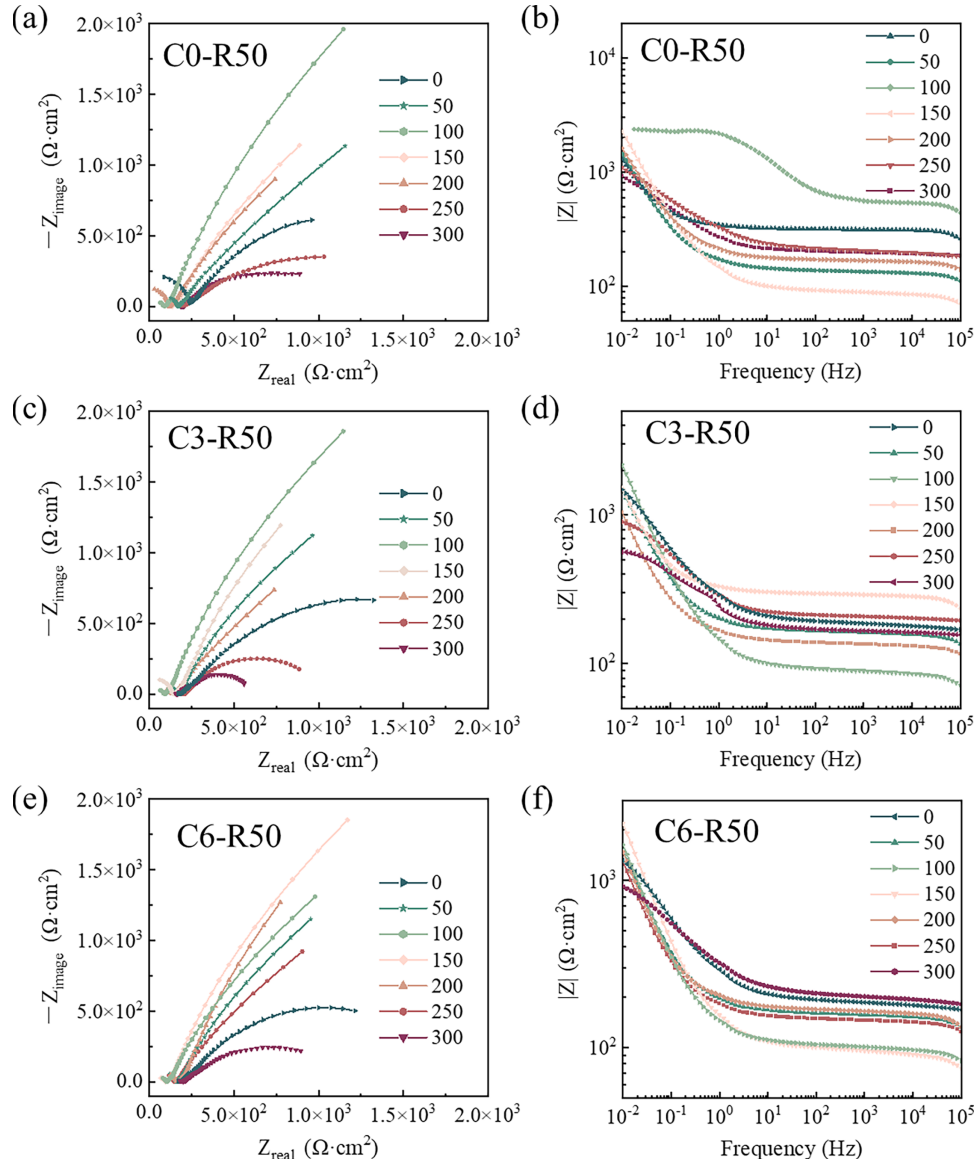


Figure 8: EIS responses of reinforced concrete specimens with RAC during dry-wet cycles: nyquist and bode plots for (a,b) C0-R50, (c,d) C3-R50, and (e,f) C6-R50 groups.

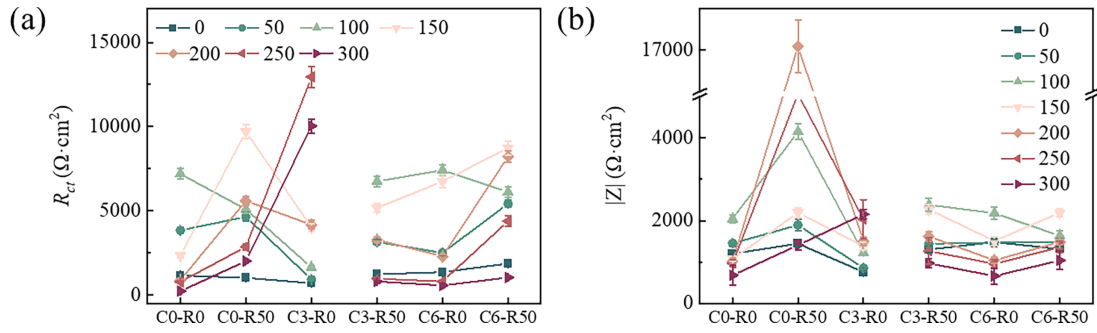


Figure 9: Variations of charge transfer resistance and low-frequency impedance modulus with dry-wet cycles for different specimens: (a) variation curve of R_{ct} ; (b) variation curve of $|Z|$.

The incorporation of RAC generally reduces the long-term durability of the protective film, while the addition of nano-SiO₂ can effectively mitigate this negative effect. A comparison between C0-R0 and C0-R50 (50% RAC) shows that although the $|Z|$ of both groups decreased after 300 cycles, the C0-R50 group exhibited more drastic fluctuations during 100–200 cycles, indicating poorer stability of its passive film. This instability in the EIS response directly corresponds to the sharp drop in OCP observed around 150 cycles for C0-R50, signaling the transition from a passive state to active corrosion. This is mainly because the high porosity and internal microcracks of RAC provide convenient channels for corrosive media (O₂, H₂O, and CO₂) to reach the steel-concrete interface, putting the passive film in a frequent dynamic balance of damage and re-passivation. Nevertheless, it is worth noting that in the R50 group, the specimen incorporated with 6% nano-SiO₂ (C6-R50) still maintained a high $|Z|$ of 2191.1 Ω·cm² at 150 cycles, which was superior to that of the unmodified C0-R50 group. This confirms that nano-SiO₂ has a significant repairing effect on the microdefects caused by RAC; by improving the overall impermeability of recycled concrete, nano-SiO₂ indirectly enhances the $|Z|$ on the steel surface.

3.4 Porosity Analysis

Total porosity is a critical microstructural parameter that dictates the macro-durability of concrete. Fig. 10 presents the evolution of total porosity for various specimens as a function of RAC replacement ratio and nano-SiO₂ dosage. The incorporation of 50% RAC (C0-R50) resulted in a significant increase in total porosity, rising from 14.2 (±0.6)% in the control group (C0-R0) to 16.8 (±0.8)%. This 18.3% increment is primarily attributed to the inherent porosity of the adhered old mortar and the multi-layer ITZs characteristic of recycled aggregates. The structural defects reflected by high porosity established a clear causal link with the deteriorated electrochemical performance. Specifically, the high-porosity matrix of C0-R50 failed to provide sufficient physical shielding, leading to the highest cumulative mass loss (0.215 g) and a rapid drop in OCP. This is further validated by the EIS results in Section 3.3, where the R_{ct} of C0-R50 plummeted to 807 Ω·cm² and the low-frequency impedance modulus ($|Z|$) remained the lowest among all groups. The high connectivity of pores in C0-R50 shortened the diffusion paths for oxygen and moisture, which was quantitatively manifested as a stepwise increase in i_{corr} beyond 150 cycles.

Conversely, the addition of nano-SiO₂ exhibited a pronounced “pore-refining” effect across all aggregate systems. In the R0 system, 6% nano-SiO₂ (C6-R0) reduced the porosity to a minimum of 11.4%. More importantly, in the R50 system, the porosity followed a descending trend of 16.8 (±0.8)% (C0) > 15.1 (±0.7)% (C3) > 13.6 (±0.7)% (C6). This systematic reduction in porosity directly underpins the enhancement of the steel’s corrosion resistance. For instance, the C6-R0 group, which achieved the minimum porosity of 11.4%, maintained an extremely low i_{corr} (9.70 μA/cm²) even at 300 cycles. The reduction in porosity and the

consequent refinement of pore size significantly increased the tortuosity of the matrix, which is reflected in the exponential-like recovery of R_{ct} and the superior $|Z|$ values observed in nano-modified groups.

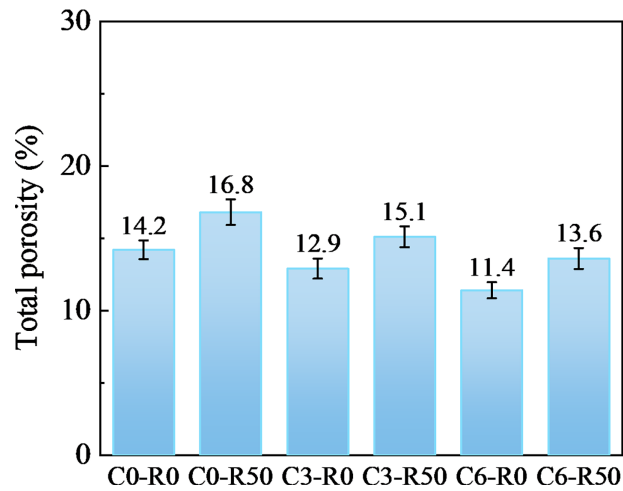


Figure 10: Test results of total porosity.

Notably, the porosity of C6-R50 (13.6 (± 0.7)%) was even lower than that of the pristine C0-R0 group (14.2 (± 0.6)%), suggesting that 6% nano-SiO₂ can fully compensate for the structural deficiencies induced by 50% RAC replacement. This microstructural “repairing effect” is consistent with the mass loss results, where the C6-R50 group showed a 13% reduction in material loss compared to the C0-R50 group. These results demonstrate that nano-SiO₂ optimizes the matrix densification, thereby effectively blocking the charge transfer process and suppressing the electrochemical corrosion kinetics under aggressive dry-wet cycles.

3.5 Mechanism of Corrosion

The dry-wet cyclic environment in the splash zone of river piers acts as the dominant external factor accelerating steel corrosion. In the wetting phase, pore water facilitates the inward transport of dissolved substances and maintains the medium for electrochemical reactions; in the drying phase, water evaporation significantly promotes the ingress of atmospheric CO₂ through the desorbed pore channels.

Under the synergistic effect of carbonation and oxygen supply, microscopic corrosion cells are established. The anode undergoes iron oxidation: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$; the cathode presents oxygen reduction: $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$. The anodic and cathodic products further react to form corrosion deposits such as $\text{Fe}(\text{OH})_3$, $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ [30] (Fig. 11). These corrosion products occupy a much larger volume than the original steel, generating expansive stress and eventually causing cracking and spalling of the concrete cover, especially in recycled aggregate concrete or structures with insufficient cover thickness. RACs retain porous old mortar and contain abundant internal microcracks, which provide preferential diffusion pathways for aggressive species such as CO₂ and O₂ and markedly reduce the corrosion resistance of recycled concrete [31]. Nano-SiO₂ improves the microstructure via two major mechanisms: the micro-filling effect refines micropores and optimizes the ITZ to block ion penetration; meanwhile, its pozzolanic reactivity consumes $\text{Ca}(\text{OH})_2$ and produces dense C-S-H gels, further densifying the matrix and enhancing interfacial bonding. Accordingly, the modified concrete effectively hinders the ingress of aggressive media and maintains stable passivation of steel bars under long-term dry-wet cycles.

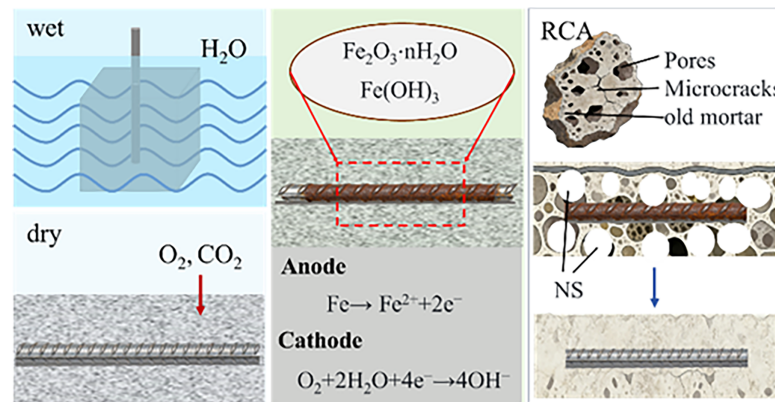


Figure 11: Schematic diagram of corrosion mechanism of steel bar in concrete with different nano-SiO₂ and recycled aggregate contents under dry-wet cycles.

In this study, a 50% replacement of recycled aggregate significantly increases porosity and permeability, accelerating depassivation and corrosion propagation. When the nano-SiO₂ content increases from 0% to 6%, both the micro-filling and pozzolanic effects are gradually enhanced, leading to refined pore structures, prolonged ion diffusion paths, and prominent inhibition of steel corrosion. Even with 50% recycled aggregate incorporation, 6% nano-SiO₂ achieves the optimum densification effect, remarkably alleviating steel corrosion and realizing the balanced improvement of environmental sustainability and durability of recycled concrete.

4 Conclusion, Limitations and Future Work

4.1 Conclusion

To clarify the effects of nano-SiO₂ content and RAC replacement on the electrochemical corrosion characteristics of reinforced recycled concrete under dry-wet cycles, 300 accelerated dry-wet cycle tests were conducted in this study. Combined with open circuit potential, linear polarization curves, and electrochemical impedance spectroscopy, the corrosion evolution and protection mechanism of steel bars in specimens with different mix proportions were systematically investigated. Based on the experimental results obtained under the specific conditions of this study (C40 concrete and 50% RAC replacement ratio), the main conclusions are summarized as follows:

1. Under dry-wet cyclic conditions, the steel bars in recycled concrete undergo a typical corrosion evolution from passivation to activation. For the unmodified RAC (50% replacement), The failure of the passive film occurs at approximately 150 cycles for unmodified recycled concrete. The incorporation of nano-SiO₂ significantly delays the carbonation-induced depassivation of steel bars, with the 6% dosage group showing the highest impedance and lowest corrosion current among the tested specimens.
2. The results of corrosion current density, steel mass loss, and electrochemical impedance consistently demonstrate that a 50% RAC replacement remarkably accelerates the corrosion process. Within the investigated range, nano-SiO₂ effectively compensates for the inherent structural defects of recycled aggregates, and its inhibition effect strengthens with increasing dosage. Specifically, 6% nano-SiO₂ greatly reduces the corrosion rate of steel reinforcement.
3. The microstructural optimization provided by nano-SiO₂—namely the pozzolanic reaction and physical filling—reduces the connectivity of the pore structure. This modification limits the transport of CO₂

and oxygen, thereby enhancing the corrosion resistance of the reinforced RAC under the laboratory-simulated dry-wet cycles.

4.2 Limitations and Future Work

It should be noted that the findings of this study are based on a specific concrete strength class (C40) and a fixed RAC replacement level (50%). While these results demonstrate the potential of nano-SiO₂ in enhancing the durability of RAC in low-chloride environments, the “optimal” dosage and performance may vary with different aggregate qualities and water-binder ratios. Future research is suggested to cover a broader range of strength grades and long-term field exposure to further validate these laboratory findings.

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Availability of Data and Materials: Data available on request from the authors. The data that support the findings of this study are available from the corresponding author, Deqiang Yang, upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Liu F, Zhang T, Luo T, Zhou M, Zhang K, Ma W. Study on the deterioration of concrete under dry–wet cycle and sulfate attack. *Materials*. 2020;13(18):4095. doi:10.3390/ma13184095.
2. Song Y, Wu Q, Agostini F, Skoczylas F, Bourbon X. Concrete shrinkage and creep under drying/wetting cycles. *Cem Concr Res*. 2021;140(4):106308. doi:10.1016/j.cemconres.2020.106308.
3. Xue W, Chen J, Xu F, Jiang AY. Corrosion development of carbon steel grids and shear connectors in cracked composite beams exposed to wet-dry cycles in chloride environment. *Materials*. 2018;11(4):479. doi:10.3390/ma11040479.
4. Li Z, Wang Y, Sun X, Liu B, Wang Y. Experimental investigation on the effects of temperature and w/c on corrosion characteristics of rebars in concrete exposed to salt lake environments. *J Mater Sci*. 2024;59(33):15786–801. doi:10.1007/s10853-024-10083-y.
5. Angst U, Elsener B, Larsen CK, Vennesland Ø. Critical chloride content in reinforced concrete—a review. *Cem Concr Res*. 2009;39(12):1122–38. doi:10.1016/j.cemconres.2009.08.006.
6. Asaad MA, Huseien GF, Baghban MH, Raja PB, Fediuk R, Faridmehr I, et al. Gum Arabic nanoparticles as green corrosion inhibitor for reinforced concrete exposed to carbon dioxide environment. *Materials*. 2021;14(24):7867. doi:10.3390/ma14247867.
7. Li M, Liu H, Li B, Gong S, Xu C, Su T, et al. Frost resistance and damage mechanism of recycled aggregate concrete. *Coatings*. 2025;15(10):1169. doi:10.3390/coatings15101169.
8. Fernandes B, Carré H, Mindeguia JC, Perlot C, La Borderie C. Spalling behaviour of concrete made with recycled concrete aggregates. *Constr Build Mater*. 2022;344:128124. doi:10.1016/j.conbuildmat.2022.128124.
9. Ouyang K, Liu J, Liu S, Song B, Guo H, Li G, et al. Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: a review. *Resour Conserv Recycl*. 2023;188(2018):106717. doi:10.1016/j.resconrec.2022.106717.
10. Ramalingam M, Sivamani J, Narayanan K. Performance studies on recycled aggregate concrete with treated recycled aggregates. *Waste Dispos Sustain Energy*. 2023;5(4):451–9. doi:10.1007/s42768-023-00157-z.

11. Elsheikh A, Al-Zayadi SK, Albo-Hassan AS. Experimental investigation of concrete incorporating recycled concrete aggregates. *Innov Infrastruct Solut.* 2024;9(6):194. doi:10.1007/s41062-024-01486-6.
12. Younis KH. Metakaolin modified recycled aggregate concrete containing recycled steel fibers. *Mater Today Proc.* 2021;45(49):4689–94. doi:10.1016/j.matpr.2021.01.120.
13. Al-Kheetan MJ, Jweihan YS, Rabi M, Ghaffar SH. Durability enhancement of concrete with recycled concrete aggregate: the role of nano-ZnO. *Buildings.* 2024;14(2):353. doi:10.3390/buildings14020353.
14. Gao C, Huang L, Yan L, Jin R, Chen H. Mechanical properties of recycled aggregate concrete modified by nano-particles. *Constr Build Mater.* 2020;241(12):118030. doi:10.1016/j.conbuildmat.2020.118030.
15. Li G, Zhuang Z, Lv Y, Wang K, Hui D. Enhancing carbonation and chloride resistance of autoclaved concrete by incorporating nano-CaCO₃. *Nanotechnol Rev.* 2020;9(1):998–1008. doi:10.1515/ntrev-2020-0078.
16. Mukharjee BB, Barai SV. Influence of incorporation of nano-silica and recycled aggregates on compressive strength and microstructure of concrete. *Constr Build Mater.* 2014;71(2):570–8. doi:10.1016/j.conbuildmat.2014.08.040.
17. Rajput B, Pimplikar SS. Influence of nano silica on durability properties of concrete. *Innov Infrastruct Solut.* 2022;7(2):180. doi:10.1007/s41062-022-00777-0.
18. Liu R, Xiao H, Geng J, Du J, Liu M. Effect of nano-CaCO₃ and nano-SiO₂ on improving the properties of carbon fibre-reinforced concrete and their pore-structure models. *Constr Build Mater.* 2020;244(3):118297. doi:10.1016/j.conbuildmat.2020.118297.
19. Feng H, Shen S, Pang Y, Gao D, Wang Z, Sheikh MN. Mechanical properties of fiber and nano-Al₂O₃ reinforced magnesium phosphate cement composite. *Constr Build Mater.* 2021;270(4):121861. doi:10.1016/j.conbuildmat.2020.121861.
20. Joshaghani A, Balapour M, Mashhadian M, Ozbakkaloglu T. Effects of nano-TiO₂, nano-Al₂O₃, and nano-Fe₂O₃ on rheology, mechanical and durability properties of self-consolidating concrete (SCC): an experimental study. *Constr Build Mater.* 2020;245:118444. doi:10.1016/j.conbuildmat.2020.118444.
21. Wang X, Cheng F, Wang Y, Zhang X, Niu H. Impact properties of recycled aggregate concrete with nanosilica modification. *Adv Civ Eng.* 2020;2020(1):8878368. doi:10.1155/2020/8878368.
22. Ying J, Zhou B, Xiao J. Pore structure and chloride diffusivity of recycled aggregate concrete with nano-SiO₂ and nano-TiO₂. *Constr Build Mater.* 2017;150(2):49–55. doi:10.1016/j.conbuildmat.2017.05.168.
23. Rivera-Corral JO, Fajardo G, Arliguie G, Orozco-Cruz R, Deby F, Valdez P. Corrosion behavior of steel reinforcement bars embedded in concrete exposed to chlorides: effect of surface finish. *Constr Build Mater.* 2017;147(10):815–26. doi:10.1016/j.conbuildmat.2017.04.186.
24. Beglarigale A, Yiğiter H, Yazıcı H. Corrosion performance of various reinforced concretes subjected to a systematic wetting-drying cycle regime in real marine environment. *J Mater Civ Eng.* 2023;35(5):04023056. doi:10.1061/(asce)mt.1943-5533.0004707.
25. Abousnina R, Aljuaydi F, Benabed B, Almabrok MH, Vimonsatit V. A state-of-the-art review on the influence of porosity on the compressive strength of porous concrete for infrastructure applications. *Buildings.* 2025;15(13):2311. doi:10.3390/buildings15132311.
26. Zhang P, Sha D, Li Q, Zhao S, Ling Y. Effect of nano silica particles on impact resistance and durability of concrete containing coal fly ash. *Nanomater.* 2021;11(5):1296. doi:10.3390/nano11051296.
27. Ali D, Sharma U, Singh R, Singh LP. Impact of silica nanoparticles on the durability of fly ash concrete. *Front Built Environ.* 2021;7:665549. doi:10.3389/fbuil.2021.665549.
28. Gómez-Soberón JMV. Porosity of recycled concrete with substitution of recycled concrete aggregate an experimental study. *Cem Concr Res.* 2002;32(8):1301–11. doi:10.1016/S0008-8846(02)00795-0.
29. Yan Y, Zhu H, Fan Z, Zhao J, Jiang S. Corrosion behavior of reinforcing steel in the immersed tube tunnel (ITT) under submarine environment. *Materials.* 2023;16(9):3300. doi:10.3390/ma16093300.
30. Ahmad S. Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review. *Cem Concr Compos.* 2003;25(4–5):459–71. doi:10.1016/S0958-9465(02)00086-0.
31. Xiao J, Li W, Fan Y, Huang X. An overview of study on recycled aggregate concrete in China (1996–2011). *Constr Build Mater.* 2012;31(5):364–83. doi:10.1016/j.conbuildmat.2011.12.074.